Strong Color Field Baryonic Remnants in Nucleus-Nucleus Collisions at 200A GeV.

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The effects of strong color electric fields (SCF) on the baryon production at RHIC are studied in the framework of HIJING/B$\bar{\rm B}$ (v2.0) model. The particle species dependence of nuclear modification factors (NMF) are analyzed for Au+Au collisions at 200A GeV. A doubling of the string tension leading to a modification of the strangeness suppression according to Schwinger mechanism is shown to provide an alternate explanation to coalescence models for the interpretation of the observed baryon and meson production at moderate p_T and results in a predicted enhancement in the (multi)strange (anti)hyperon production.

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I. INTRODUCTION

While the phase transition from hadronic degree of freedom to partonic degrees of freedom (quarks and gluons) in ultra-relativistic nuclear collisions is a central focus of recent experiments at the Relativistic Heavy Ion Collider (RHIC), data on baryon and hyperon production has revealed interesting and unexpected features at RHIC that may be of novel dynamical origin instead. The so called *baryon/meson anomaly* [1–4] is observed as a large enhancement of the baryon to meson ratio and a large difference of the nuclear modification factor (NMF) between total charged [5] and neutral pions (π^0) [6] at moderate transverse momenta ($2 < p_T < 5$ GeV/c).

In a previous paper [7] we studied the possible role of topological baryon junctions [8] in nucleus-nucleus collisions. We have shown in the framework of HIJING/B$\bar{\rm B}$ v2.0 model, that junction-antijunction (J$\bar{\rm J}$) loops with an enhanced *intrinsic transverse momentum* $k_T \approx 1$ GeV/c, a default string tension $\kappa_0 = 1$ GeV/fm, and a di-quark suppression factor (PARJ(1)=γ_{qq}=0.07) provide a partial explanation of the baryon/meson anomaly [7]. That model therefore provides an alternative dynamical explanation of the data to recombination models [9]. Within HIJING/B$\bar{\rm B}$ v2.0 [7] one of the main assumptions is: the strings could survive and fragment [12,13], and in particular populate the mid to low p_T range. In contrast, in the recombination picture [9] or in hydrodynamical approach [14] all coherent strings are assumed to become rapidly incoherent resulting in rapid thermalization.

In this paper we explore further dynamical effects associated with long range coherent fields (i.e strong color fields, SCF) including baryon junctions [8] and loops [10] that may arise in nuclear reactions. Our emphasis here will be on the novel baryon observables measured at RHIC. In nucleus-nucleus collisions the color charge excitations may be considerably greater than in nucleon-nucleon collisions due to the almost simultaneous interaction of several participating nucleons in a row [11,12]. Molecular dynamics models [15–17] have been used to study the effects of color ropes as an effective description of the non-perturbative, soft gluonic part of QCD [18–20]. Strangeness enhancement [21–29], strong baryon transport [30], and increase of intrinsic k_T [19] are all expected consequences of SCF. This can be modeled in microscopic models as an increase of the effective string tension that controls the $q\bar{q}$ and $qq\overline{qq}$ pair creation rates and strangeness suppression factors [11].

For a uniform chromoelectric flux tube with field (E) the probability to create a pair of quarks with mass (m), effective charge (e), and transverse momentum (p_T) per unit time per unit volume is given by [31] :

$$P(p_T)\, d^2p_T = -\frac{|eE|}{4\pi^3} ln\left\{1 - exp\left[-\frac{\pi(m^2+p_T^2)}{|eE|}\right]\right\} d^2p_T \tag{1}$$

The integrated probability (P_m) reproduces the classical Schwinger results [32] , derived in spinor quantum electrodynamics (QED) for e^+e^- production rate, when the leading term in Eq. 2 is taken into account, i. e.:

$$P_m = \frac{(eE)^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2} exp\left(-\frac{\pi\, m^2 n}{|eE|}\right) \tag{2}$$

In general in microscopic string models the heavier flavors (and di-quark) are suppressed according to Schwinger formula [32]:

$$\gamma_Q = \frac{P(Q\bar{Q})}{P(q\bar{q})} = exp\left(-\frac{\pi(m_Q^2 - m_q^2)}{\kappa}\right) \tag{3}$$

where $\kappa = |eE|$ is the *string tension*; m_Q is the effective quark mass; (Q=s for strange quark; Q=qq for a di-quark), and q=u,d are the light nonstrange quarks.

In the case of quark-gluon plasma (QGP) creation it is necessary to modify the dynamics of particle vacuum production at short time scales, and the abundance of newly

produced particle may deviate considerably from the values obtained for the constant field [33]. Two possible processes may lead to an increase of strangeness production within the framework of Schwinger mechanism are: i) increasing the field strength by a modified string tension (κ) [11,19,25,26,34], or ii) dropping the quark masses due to chiral symmetry restoration [35,34,36,37]. A specific chiral symmetry restoration could be induced by a rapid deceleration of the colliding nuclei [38].

Present estimates [39] of the *current quark masses* range from: m_u =1.5-5 MeV; m_d=3-9 MeV, m_s=80-190 MeV. For di-quark we consider m_{qq}=450 MeV [40]. Taking for constituent quark masses of light non-strange quark $M_{u,d}$= 230 MeV, strange quark M_s=350 MeV [41], and di-quark mass M_{qq}=550 $\pm$ 50 MeV as in Ref. [40], it is obvious that the masses of (di)quark and strange quark will be substantially reduced at the chiral phase transition. If the QGP is a chirally restored phase of strongly interacting matter, in this picture the production of strange hadrons will be enhanced [37]. In this case a possible decrease of the strange quark mass would lead to a similar enhancement of the suppression factors, obtained (in microscopic models) by an increase of string tension [18,19,34,33,36]. Moreover, if we consider that Schwinger tunneling could explain the thermal character of hadron spectra and that, due to SCF effects the string tension value κ fluctuates we can define an apparent temperature $T = \sqrt{< \kappa > /2\pi}$ [42].

II. OUTLINE OF THE HIJING/B$\bar{\text{B}}$ V2.0 MODEL

Our analysis are performed in the framework of HIJING/B$\bar{\text{B}}$ v2.0 model [7] that is based on HIJING/B$\bar{\text{B}}$ v1.10 [43]. Multiple hard and soft interactions proceed as in HIJING v1.37 [44]. In HIJING/B$\bar{\text{B}}$ v2.0 we introduced [7] the possible topology with two junctions [47], and a new algorithm where $J\bar{J}$ loops are modeled by an enhancing di-quark p_T kick characterized by a gaussian width of $\sigma_{qq}{}' = f \cdot \sigma_{qq}$ = 1.08 GeV/c, with σ_{qq}=0.360 GeV/c (consistent with PYTHIA [45] default value), i.e. f=3, which we fit to best reproduce the observed p_T spectrum of the baryons.

Following the equations above, we take into account SCF in our model by an *in medium effective string tension* $\kappa > \kappa_0$, which lead to new values for the suppression factors, as well as the new effective intrinsic transverse momentum k_T [18–20]. This includes: i) the ratio of production rates of di-quark to quark pairs (di-quark suppression factor), $\gamma_{qq} = P(qq\overline{qq})/P(q\bar{q})$, ii) the ratio of production rates of strange to nonstrange quark pairs (strangeness suppression factor), $\gamma_s = P(s\bar{s})/P(q\bar{q})$, iii) the extra suppression associated with a diquark containing a strange quark compared to the normal suppression of strange quark (γ_s), $\gamma_{us} = (P(u\bar{u}s\bar{s})/P(u\bar{u}d\bar{d}))/(\gamma_s)$, iv) the suppression of spin 1 diquarks relative to spin 0 ones (appart from the factor of 3 enhancement of the former based on counting the number of spin states), γ_{10}, and v) the (anti)quark ($\sigma''_q = \sqrt{\kappa/\kappa_0} \cdot \sigma_q$) and (anti)diquark ($\sigma''_{qq} = \sqrt{\kappa/\kappa_0} \cdot f \cdot \sigma_{qq}$) gaussian width. These parameters correspond to γ_{qq}=PARJ(1), γ_s=PARJ(2), γ_{us}=PARJ(3), γ_{10}=PARJ(4), and σ_{qq}= PARJ(21) of the JETSET7.3 subroutines [45]. Our calculations are based on the assumption that the effective enhanced string tension (κ), in both basic ropes ($q^n - \bar{q}^n$) and junction ropes ($q^n - q^n - q^n$) are the same. For elementary n strings and junctions this ansatz is supported by baryon studies [46]. A different approach to baryon production without baryon junctions has been proposed in [25] where SCF from string fusion process can lead to $(qq)_6 - (\bar{q}\bar{q})_{\bar{6}}$ with about double the string tension. Both types of SCF configurations may arise but predict different rapidity dependence of the valence baryons. We consider in this version 2.0 of HIJING B$\bar{B}$ only baryon junction rope loops.

There is a debate in the study of qqq system on the shape of Δ-like geometry and Y-like geometry [47], [48], and on the stability of these configurations for the color electric fields [49]. In both topologies we expect a higher string tension than in an ordinary $q\bar{q}$ string ($\kappa_Y = \sqrt{3}\,\kappa_0$ and $\kappa_\Delta = (3/2)\,\kappa_0$). It was shown [49] that the total string tension has neither the Y nor the Δ-like value, but lies rather in-between the two pictures. However, the Y configuration appears to be a better representation of the baryons . If two of these quarks stay close together, they behave as a di-quark [48]. In a dual superconductor models of color confinement for the Y-geometry the flux tubes converge first toward the centre of the triangle and there is also another component which run in opposite direction. They attract each other and this lower the energy of Y-configuration [47].

Phenomenological applications are currently based on Regge trajectory which gives the appropiate relationship between the mass M of the hadrons and its spin J_s: $J_s = \alpha + \alpha_s\, M^2$, where $\alpha \simeq 0.5$ is the Regge intercept; α_s is the Regge slope. The value of the Regge slope for baryons is $\alpha_s \simeq 1\ GeV^{-2}$ [43] that yields a string tension (related to the Regge slope, $\kappa_0 = 1/2\pi\alpha_s$ [50]) $\kappa_0 \approx$1 GeV/fm. This value is taken in our calculations within HIJING/B$\bar{\text{B}}$ v2.0 toghether with the following values for the suppression factors correponding to the constituent quark masses given above: γ_{qq} =0.02; γ_s=0.30; γ_{us}=0.40; γ_{10}=0.05. A broadening in k_T is chosen as: σ_q=0.360 GeV/c and σ'_{qq} = 1.08 GeV/c (i.e f=3). HIJING/B$\bar{\text{B}}$ v2.0 predictions using this set of parameters are labeled here by w/o SCF, i.e. without strong color field, or by κ_0=1 GeV/fm.

The multi-gluon exchange processes dominated by Pomeron exchange in high energy nucleus-nucleus collisions could be described by a Regge trajectory with a smaller slope $\alpha_s{}' \approx 0.45$ GeV^{-2} [51], leading to an increase of string tension to $\kappa \approx 2\,\kappa_0$ [19], corresponding to an increasing values for the suppression factors: γ'_{qq}=0.12; $\gamma_s{}'$=0.55; $\gamma_{us}{}'$=0.63, $\gamma_{10}{}'$=0.12 as well as of a broadening in k_T , σ''_q=0.500 GeV/c and σ''_{qq} = 1.5

GeV/c. The results obtained with this set of parameters are labeled here w/SCF, i.e. with strong color field, or by κ= 2 GeV/fm. We note, that the increase of "intrinsic k_T" (the gaussian width σ''_{qq}), is strongly supported by recent experimental values reported by PHENIX [52], which show an increase from p+p (k'_{Ty}=1.08 $\pm$ 0.05 GeV/c) to d+Au collisions (k''_{Ty}=1.36 $\pm$ 0.07 $\pm$ 0.12 GeV/c) at $\sqrt{s_{NN}}$=200 GeV.

III. NUCLEAR MODIFICATION FACTORS

Here we will concentrate our analysis on species dependence of the nuclear modification factors (NMF) R_{AA} and R_{cp} in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. R_{AA} is the ratio of the heavy-ion yield to the pp cross section normalized by the number of binary collisions, while R_{cp} is the ratio of scaled central to peripheral particle yield and are defined as in Ref. [7]. For p+p interactions we have used in our calculations, the set of optimized parameters from PYTHIA [45] or HIJING [44].

Figure 1 shows the predicted NMF R_{AA} for the sum of hadrons for two centralities. The results are compared to the data obtained by the PHENIX collaboration [53]. The data at both centralities could not be described by assuming only a broadening of the *intrinsic* k_T from its standard value (dotted histograms) to σ'_{qq}=1.08 GeV/c (i.e f=3, dashed histograms). The introduction of SCF has an effect on the predicted nuclear modification factors of the total inclusive hadrons and results in a better agreement with data (solid histograms). The data indicate at most a small variation with centrality of the factor "f" consistent with the broadening originating at the parton level.

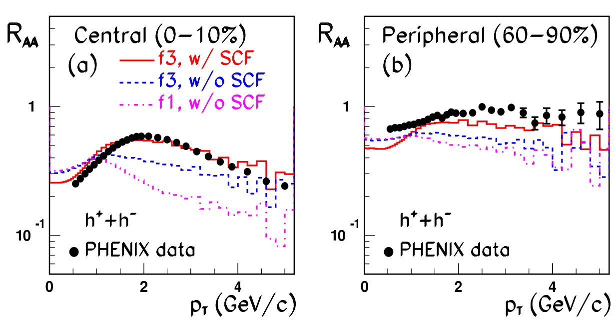

FIG. 1. (Color online) Comparison of HIJING/B$\bar{\text{B}}$ v2.0 predictions for R_{AA} of total inclusive charged hadrons, in central (0-10% -left) and peripheral (60-90%-right) Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The results are with (solid histograms) and without SCF (dashed histograms). The label f3 stands for model calculations assuming f=3. Dashdotted histograms are the results without SCF and f=1 (label f1). The data are from PHENIX [53]. Only statistical error bars are shown.

In order to better quantify possible effects of strong color field on particle production we investigate species dependence of NMFs $R_{AA}(p_T)$ for central collisons (Fig. 2a-d.), where higher sensitivity to SCF is expected. Because of their dominance, the production of pions is only moderately modified when we consider an increase of the string tension value, since the total energy is conserved. Taking into account SCF effects (solid histograms) results in changes at moderate p_T of less than $\approx$ 20% for the pion yield (Fig. 2a). The scaling behaviour in $R_{AA}(p_T)$ of the pions is different from those of the sum of protons and anti-protons (Fig. 2c). The pions yield in central events is strongly suppressed compared to binary collisions scaling ($R_{AA}(p_T)$=1).

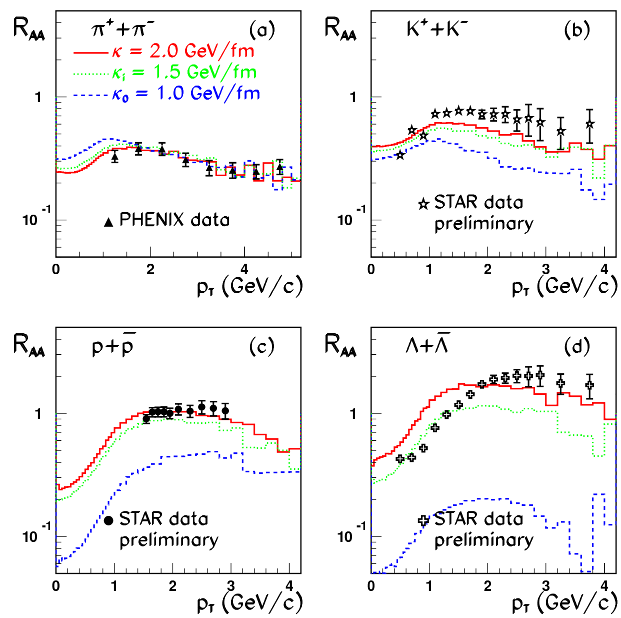

FIG. 2. (Color online) HIJING/B$\bar{\text{B}}$ v2.0 predictions for species dependence of NMF (R_{AA}) in central (0-10%) Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV: (a) for charged pions, (b) kaons, (c) inclusive p+$\bar{\text{p}}$, (d) inclusive $\Lambda + \bar{\Lambda}$. The results are with (solid histograms) and without SCF (dashed histograms). The dotted histograms are the predictions assuming κ_i=1.5 GeV/fm. The data are from PHENIX [54] and STAR [55,56] collaborations. Only statistical error bars are shown.

The hadron production in HIJING/B$\bar{\text{B}}$ v2.0 is mainly from the fragmentation of energetic partons. Thus, the observed suppression of pions in central collisions may be a signature of the energy loss of partons during their propagation through the hot and dense matter (possibly QGP) created in the collisions, i.e *jet quenching*. On the contrary, strange particles are highly sensitive to the presence of SCF. Kaons (Fig. 2b) and lambda (Fig. 2d), show an increase by a factor of two and ten, respectively. Such an increase results in a predicted enhancement of the lambda yield relative to scaled binary collisions as opposed to the strong suppression predicted (and observed) for pions. These results are consistent with the PHENIX data [54] and preliminary STAR data [55,56]. In or-

der to study the sensitivity to string tension values we also present the results corresponding to an intermediate value of the string tension i.e. κ_i= 1.5 GeV/fm (dotted histograms). The discrepancy seen at low $p_T < 1.2$ GeV/c (solid histograms) comes from a sizeable contribution from radial flow, not included in our model. The low p_T region at RHIC seems to be better described within hydodynamical approach [14].

The predicted particle dependence is due to the interplay between nuclear effects such as jet quenching and shadowing and fluctuations of the chromoelectric field in the early phase of the reaction. Insight into the source of the particle dependence is obtained from Fig. 3 and Fig. 4. The comparison of the NMF $R_{cp}(p_T)$ for protons and pions (Fig. 3a) as well as for kaons (Fig. 3c) presents a behavior similar to $R_{AA}(p_T)$, i.e shows a meson/baryon anomaly that is well described and was interpreted in [7] as due to a possible exotic gluonic mechanism (J$\bar{\text{J}}$ loops).

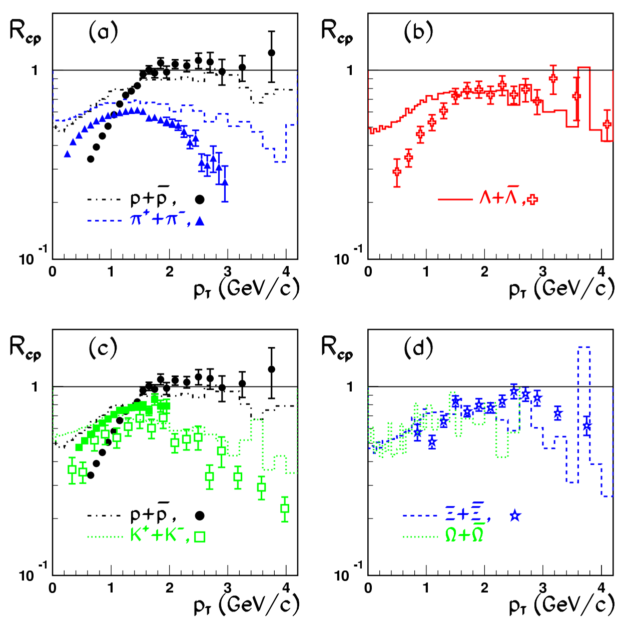

FIG. 3. (Color online) HIJING/B$\bar{\text{B}}$ v2.0 w/SCF (κ = 2 GeV/fm) predictions for species dependence of NMFs $R_{cp}(p_T)$ in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The results are for scaled (0-10%)/(60-90%). The data are from PHENIX (filled symbols) and from STAR (open symbols). PHENIX data are scaled (0-10%)/(60-90%) [2]. STAR data are at slightly different centralities: scaled (0-5%)/(60-80%) for kaons and $\Lambda's$ [57], and scaled (0-5%)/(40-60%) for Ξ (preliminary data) [55]. Only statistical error bars are shown.

In Ref. [9] it is suggested that the behavior of $R_{cp}(p_T)$ may be interpreted as due to the competition between recombination and parton fragmentation. The results obtained for $R_{cp}(p_T)$ for the strange (Fig. 3b) and multi-strange particles (Fig. 3d) show a small suppression relative to binary scaling, consistent with the experimental results for Λ [2,57], and preliminary data for Ξ [55].

In contrast, the equivalent predictions of $R_{AA}(p_T)$ for protons and (multi)strange particles (Fig. 4) show a predicted strong enhancement of NMF due to SCF effects dependent on the mass and strangeness content of the produced particles.

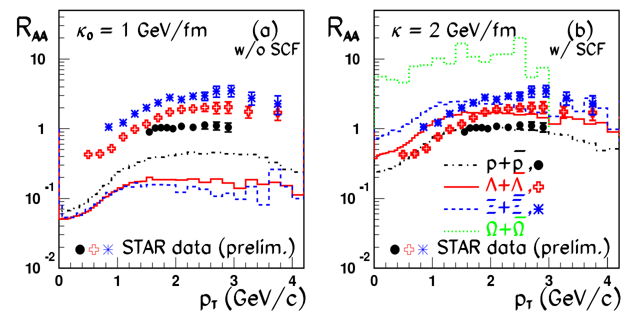

FIG. 4. (Color online) HIJING/B$\bar{\text{B}}$ v2.0 predictions with SCF (right) and without SCF (left) for species dependence of $R_{AA}(p_T)$ in central (0-5 %) Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The preliminary STAR data are from [55,56]. Only statistical error bars are shown.

In particular, the model predicts a dramatic enhancement in the multi-strange (anti-)hyperon production at moderate p_T, up to a factor of roughly 2 (relative to binary scaling) for Ξs and up to a factor of more than 10 for Ωs (Fig. 4b). The striking difference between R_{AA} and R_{cp} could be explained in our model as a consequence of SCF which manifest in both central and peripheral collisions. This shows that there is a clear difference between using peripheral Au+Au yields (as in R_{cp}), or p+p yields (as in R_{AA}) as base-line for comparison with binary collisions scaling (R_{AA}=R_{cp}=1).

IV. SUMMARY AND CONCLUSIONS

In summary, we studied the influence of possible strong longitudinal color fields in particle production in heavy-ion collisions. We modeled SCF effects within HIJING/B$\bar{\text{B}}$ v2.0, by varying the effective string tension that controls the $q\bar{q}$ and $qq\overline{qq}$ pair creation rates and strangeness suppression factors. We show that junction-(anti)junction loops and a higher string tension $\kappa = 2\,\kappa_0$ ($\kappa_0 \approx 1$ GeV/fm), could be important dynamical mechanisms in the solution of the observed *baryon/meson anomaly*. Our approach has the advantage of correlating many observables in the same dynamical model including pions, kaon, and baryons productions and of predicting species dependence of the nuclear modification factors $R_{AA}(p_T)$ and $R_{cp}(p_T)$, and the transverse momenta over a large p_T range. A greater sensitivity to SCF effects is predicted for the nuclear modification factors of (multi)strange hyperons. In particular, the measurement of Ω and $\bar{\Omega}$ yields would provide an important test of the consistency of SCF and baryon junction mechanisms at RHIC.

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